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Soundscape design and mapping of water features used over road traffic noise

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In order to develop a better understanding of the soundscape design of water features, this paper examines the effectiveness of different water structures used over road traffic noise for promoting relaxation. The work presented focuses in particular on sound mapping design, in view of identifying how appropriate water sound levels can be achieved through different designs. The analysis was carried out for a wide range of small to medium sized features typically used in gardens or parks, and sound maps of the water generated sounds were developed through the use of propagation models based on either point or line sources. Three acoustic zones ('water sound dominant zone', 'relaxation zone' and 'road traffic noise dominant zone') were defined by taking into account quantitative criteria based on water features' perception. For example, the 'relaxation zone' was defined as the zone where water sound levels are similar or not less than 3 dB below road traffic noise, based on preference findings. The three zones were calculated over a 20 m × 20 m area for all the waterscapes considered, and for a range of different road traffic noise levels. This allowed identifying optimal distances from the features where relaxation can be promoted.

1 INTRODUCTION

In the European Union, about 40% of the population is exposed to road traffic noise which is inducing adverse consequences to human well-being.¹ The Environmental Noise Directive (END)² introduced a common approach intended "to avoid, prevent or reduce on a prioritised basis the harmful effects, including annoyance, due to the exposure to environmental noise". This refers not only to the quieting of already noisy areas, but also to the protection of quiet areas against increases of environmental noise.³ In this context, the acoustic use of water generated sounds has been widely recognised as a potential mean for masking annoying urban noise⁴⁻¹² by taking advantage of their distracting effect as "wanted" sounds,⁴ as well as improving soundscape perception due to their inherent positive qualities.¹²

The principles and concepts applied to water features' design have typically focused on the central visual-aesthetic aspects of the water structures, the settings and available space, the type

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of installations and features components such as basin, pumps or the water system distribution. Therefore, little attention has often been paid to acoustic criteria at the very early stage of the design process, relegating the problem to acoustic-post design consulting. Acoustic criteria did not always appear to have figured in water features' design and this failure can presumably be attributed to a lack of knowledge of how to predict and plan the effectiveness of acoustic masking in any particular setting.¹³

In soundscape research, several efforts have been made to evaluate water sounds over road traffic noise, but only few recent studies have meticulously examined the perceptual assessment as well as the acoustical characterisation of water features used in outdoor spaces affected by road traffic noise.^{4-6,8-11,14-16} Previous studies showed that: (1) Water sounds is effective at mid-frequencies but not at low frequencies,^{4,9} although tranquillity can be also improved for low level of masking;⁴ (2) Natural streams and fountains with multiple upward jets tended to be preferred for improving relaxation, whilst waterfall sounds tended not to be liked;^{9,15} (3) Water was indicated as the preferred impact material in contrast to hard materials;⁹ (4) The preferred level of water sounds should be similar or not less than 3 dB below the road traffic noise;^{8-9,14} (5) Natural looking features tend to increase preference scores, while manmade looking features decreased them;^{4,15} (6) Auditory and visual stimuli tend to be equally dominant in water features' perception, thereby equal attention should be given to the design of both stimuli.¹⁵

In addition, a study on the masking properties of water features used over road traffic noise showed that different areas (zone of detection, zone of influence and zone of exclusion) can be identified around a water structure where the effect of water sounds is characterised by different levels of masking according to sound levels.¹³ In the zone of influence and detection, city noises can be partially or totally masked by water sounds, whilst city noises are dominant but the water structure can still attract attention acoustically in the zone of exclusion.¹³ However, this was only limited to considerations related to auditory properties of water sounds which were not supported by experimental tests. Furthermore, recent studies pointed out a positive effect of water sounds on improving the soundscape perception in a region 20-30 m around the water structure (large jet-basin jets) where the fountain sound was equally loud or louder than the road traffic noise.^{6,16}

In this context, this paper focuses on examining the effectiveness of different water structures used over road traffic noise for promoting relaxation through sound mapping design. This evaluation was made for a wide variety of small to medium sized water features (waterfalls, fountains, a cascade and streams) typically used in gardens or parks in view of identifying how appropriate water sound levels can be achieved through different designs for a range of different road traffic noise (RTN) levels. Predictions of sound pressure levels were made by using sound propagation models based on the type of sources (point or line) and presented in terms of sound maps. The predicted sound levels were then used to define acoustic areas with different levels of relaxation for each type of water structure tested. Three acoustic zones ('water sounds dominant zone', 'relaxation zone' and 'RTN dominant zone') were identified for waterscapes located in different noise settings according to sound levels. This allowed identifying optimal distances from the features where relaxation can be promoted.

2 METHODOLOGY

2.1 Water features

The waterscapes examined included small to medium sized water features that can be installed in gardens or parks as well as in indoor environments such as hotels' lobbies, and offices. The water features used in the experiment were constructed in the laboratory by Galbrun and Ali,⁹

with the exception of natural shallow streams which were tested in the field. A variety of water features were obtained by varying design parameters such as the waterfall's width, height of falling water, flow rate and impact material,⁹ as shown in Table 1.

In the study presented here, ten different water features have been selected from this pool of data to represent a wide range of water structures: a waterfall with a plain edge (PEW), a waterfall with a sawtooth edge (SEW), a waterfall with an edge made of small holes (SHW), a fountain with 37 upwards jets (FTW), a foam fountain (FF), a dome fountain (DF), a large jet (LJT), a narrow jet (NJT), a cascade with four steps (CA) and a natural shallow stream (ST), as shown in Figure 1 (showing water structures' displays placed on the same background: these images were developed and used in a previous study¹⁵ to analyse audio-visual interaction and water features' perception). Water was the only impact material chosen for the water features

Table 1 - Design and acoustic parameters of water features used in the experiment, including acoustic and psychoacoustic parameters of the sound normalized to 55 dBA. The numbers in italic refer to sounds including both road traffic noise and water sounds. Fountain extensions and jets were placed at water level, the large jet had a nozzle's diameter of 25 mm, and the narrow jet had a nozzle's diameter of 10 mm.

Sound code	Water feature type	Impact material	Flow rate (l/min)	Height (m) & Width (m)	$L_{A10}-L_{A90}$ (dB)	$L_{Ceq}-L_{Aeq}$ (dB)	Sharpness (acum)	Roughness (asper)	Pitch strength
PEW	Plain edge waterfall	Water	120	1.0 - 1.0	1.1 <i>1.4</i>	-0.3 <i>2.8</i>	1.98 <i>1.70</i>	0.03 <i>0.04</i>	0.04 <i>0.07</i>
SEW	Sawtooth edge waterfall	Water	30	0.5 - 1.0	1.0 <i>1.6</i>	-0.1 <i>2.7</i>	1.90 <i>1.59</i>	0.05 <i>0.05</i>	0.10 <i>0.07</i>
SHW	Small holes waterfall	Water	30	0.5 - 1.0	0.7 <i>1.4</i>	-1.0 <i>2.5</i>	2.23 <i>1.71</i>	0.02 <i>0.04</i>	0.09 <i>0.08</i>
FTW	Fountain (37 jets)	Water	30	-	1.4 <i>1.5</i>	-0.9 <i>2.7</i>	2.21 <i>1.67</i>	0.07 <i>0.08</i>	0.10 <i>0.08</i>
DF	Dome fountain	Water	40	-	1.2 <i>1.4</i>	-1.0 <i>2.5</i>	2.16 <i>1.70</i>	0.05 <i>0.05</i>	0.11 <i>0.08</i>
FF	Foam fountain	Stones & boulders	30	-	2.3 <i>1.6</i>	-0.2 <i>2.8</i>	1.91 <i>1.61</i>	0.09 <i>0.09</i>	0.05 <i>0.07</i>
LJT	Large jet	Water	15	-	4.9 <i>2.1</i>	4.90 <i>2.9</i>	1.73 <i>1.42</i>	0.28 <i>0.19</i>	0.08 <i>0.07</i>
NJT	Narrow jet	Water	15	-	1.9 <i>1.6</i>	-0.9 <i>2.5</i>	2.09 <i>1.67</i>	0.19 <i>0.16</i>	0.07 <i>0.08</i>
CA	Cascade (4 steps)	Stones (pebbles)	15	-	1.2 <i>1.4</i>	-1.30 <i>2.7</i>	2.21 <i>1.71</i>	0.10 <i>0.09</i>	0.05 <i>0.08</i>
ST	Natural shallow stream	Water and stones	2400	0.10-2.0	2.4 <i>1.7</i>	1.40 <i>2.5</i>	1.99 <i>1.61</i>	0.29 <i>0.21</i>	0.06 <i>0.08</i>

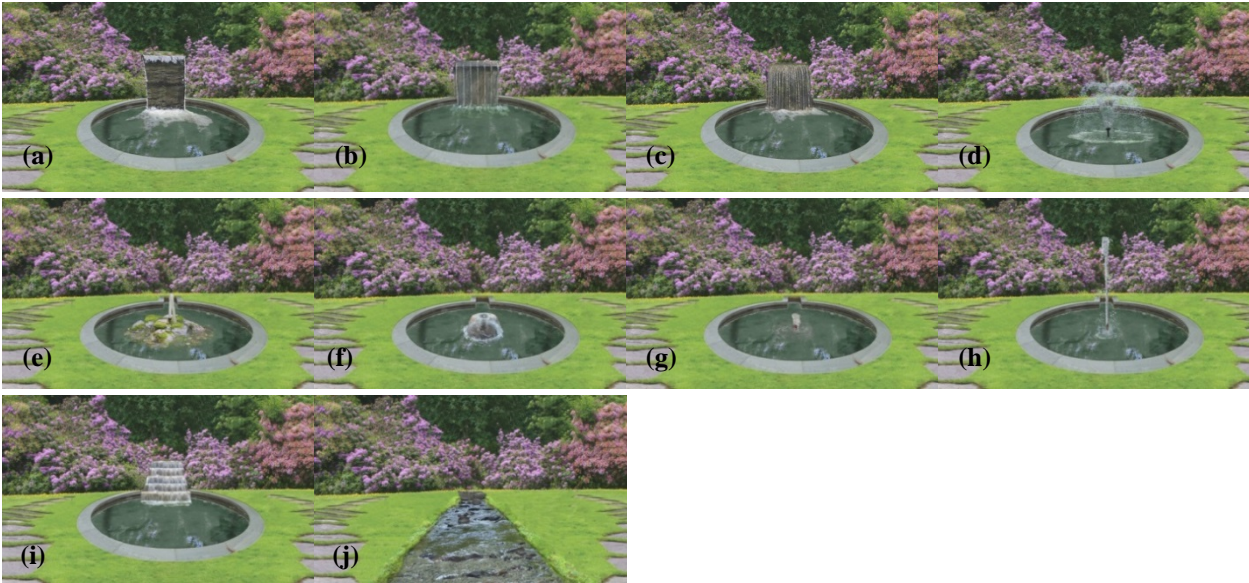
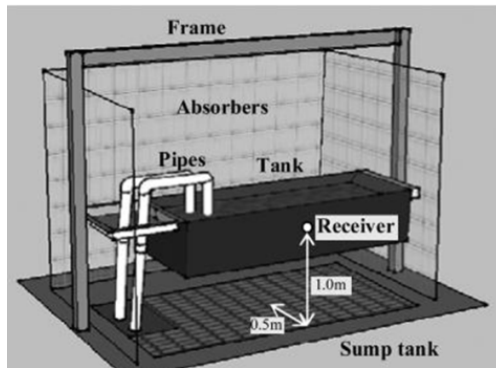


Fig. 1 - Visual displays (placed on the same background) of the water features used in the experiments. (a) PEW, waterfall with a plain edge, (b) SEW, waterfall with a sawtooth edge, (c) SHW, waterfall with small holes edge, (d) FTW, fountain with 37 upward jets, (e) FF, foam fountain, (f) DF, dome fountain, (g) LJT, large jet, (h) NJT, narrow jet, (i) CA, cascade, (j) ST, natural shallow stream.



(a) Laboratory setting



(b) Field setting

(natural shallow stream)

Fig. 2 - Setting used for sound pressure level measurements and audio recordings in the laboratory (a) and field (b).

considered in the study with the exception of CA, FF and ST, as it was found that water tends to be the preferred impact material compared to hard materials such as concrete and stones.⁹ Measurements were carried out at a distance of 0.5 m from the centre section of the basin (impact area of falling water) and 1 m above floor level for the water features tested in the laboratory,⁹ as shown in Figure 2a. On the other hand, in the case of the natural shallow stream, measurements were carried out at 2 m from the edge of the feature tested and 1 m above water (Figure 2b). In addition, acoustic and psychoacoustic parameters for both water sounds and water sounds with road traffic noise were also calculated.⁹ Binaural audio recordings of 20s were made for each water feature considered and carried out with a digital sound recorder (Zoom H4n) connected to Brüel and Kjaer Type 4190 ½ inch microphones attached to a dummy head.⁹

2.2 Propagation models

In order to design sound maps for the water features tested, sound propagation models were used for each type of sound source considered (point or line). A prediction of sound pressure levels at different receiver positions was made for each water feature located in a grid of 20 m × 20 m (Fig. 3). This grid was considered to be large enough for representing an area where small and medium sized water features can be installed (in gardens / parks). The receiver's height was set to 1.2 m above the ground as representative of a person seated in a garden or park from where she/he can hear and see a water feature in the presence of road traffic noise. Calculations were made for a grid point spacing of 1 m, assuming an ideal case scenario where sound is propagating in a semi-free field environment from a sound source placed on the ground (no reflecting surfaces along the propagation path, i.e. barriers or obstacles, with the exception of the ground surface). The propagation models included input data defining the sound power level of each water feature as well as the directivity correction and data related to attenuations occurring due to geometrical divergence, atmospheric absorption and ground effect.

According to the Rathe method,¹⁷ water generated sounds from the features tested in the laboratory (waterfalls, a cascade and fountain jets) were modelled as emitted from point sound sources. On the other hand, the natural shallow stream (ST) was the only feature studied as a line sound source.

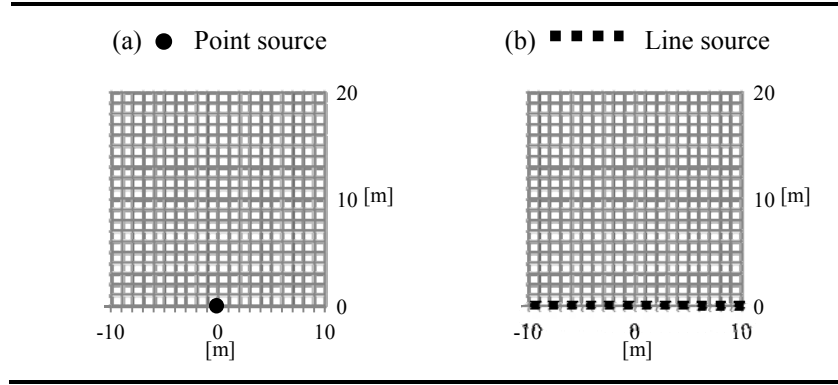


Fig. 3 - Calculation grid of 20 m × 20 m and location of sound sources: (a) point source and (b) line source.

In the case of a point sound source, calculations of sound pressure levels at a receiver location (L_p) were made for the eight octave bands with nominal midband frequencies from 63 Hz to 8 kHz according to the procedure of ISO 9613¹⁸⁻¹⁹ (equation (1)).

$$L_p = L_w + D_c - A \quad (\text{dB}) \quad (1)$$

where L_w (dB re 10^{-12} W) is the octave-band sound power level produced by the sound source; D_c (dB) is the directivity correction; and A (dB) is the octave-band attenuation that occurs during propagation including effects due to geometrical divergence, atmospheric absorption and the ground effect. Assuming the absence of barriers and reflections, the attenuations related to these effects were ignored for the predictions presented in this work.

In the case of the natural shallow stream (the only line source), predictions of sound pressure levels were initially made by using two different methods: firstly, the sound source was modelled as multiple points and, secondly it was modelled as a line. In order to understand the accuracy of both methods, measurements of sound pressure levels were carried out in the field for the stream considered at different positions along the perpendicular line from the source (stream) to the receiver. With the help of the measured noise levels, a comparison with the calculated values of sound pressure levels obtained by using the two models (multiple points and line) was made. Results pointed out that the propagation model based on the line source formula shows more reliable data predictions. For that reason, calculations of sound pressure levels (L_p) for the line sound source were made using a simple line source model by adopting the following classical acoustic equation relating power to sound pressure level:

$$L_p = L_w - (10 \log d + 8) + D_c - \alpha_t d \quad (\text{dB}) \quad (2)$$

where L_w is the sound power level of the sound source (dB/m re 10^{-12} W); $10 \log d + 8$ is a term that takes into account the geometrical divergence due to cylindrical spreading of sound where d is the distance from the source to the receiver (m); D_c is the directivity index in the case of a line source radiating over a hemi-cylinder; α_t (dB/m) is the attenuation coefficient for atmospheric absorption at the exact midband frequency as shown in ISO 9613-1.¹⁸ Attenuations by additional mechanisms such as barriers and reflections were excluded in this prediction. Finally, ground attenuations (A_{gr}) were not included in the line source model because the suggested values of A_{gr} were found to be negligible for the distances considered (1-20 m, source-receiver distance).

2.3 Defining acoustic zones around water features used over road traffic noise (RTN)

In the work presented here, the concept of different acoustic zones ('water sounds dominant zone', 'relaxation zone' and 'RTN dominant zone') around water structures was introduced as the areas where different levels of relaxation can be achieved in the presence of road traffic noise (RTN). These definitions have been determined according to water sounds levels comparable to a range of different road traffic noise levels and taking in account quantitative criteria based on main findings obtained in terms of water features' perception. The criteria used for the definition of the acoustic zones are:

- The preferred noise level of water sounds should be similar or not less than 3 dB below the road traffic noise in order to improve the soundscape perception.^{8-9,14}
- A positive effect in improving soundscape perception can occur in a region around the water structure where the fountain sound was similar or below (quieter than) the road traffic noise.^{6,16}

The 'water sound dominant zone' is defined as the area close to the water structure where road traffic noise might be still audible but water sound is the principal sound (water sound level > RTN level). The 'relaxation zone' is defined here as the area where water sound levels are similar or not less than 3 dB below road traffic noise and soundscape perception can be improved in terms of relaxation and peacefulness (RTN level – 3 dBA ≤ water sounds level ≤ RTN level). The 'RTN dominant zone' is defined here as the area where people can still detect water sounds but road traffic noise is dominant (water sounds level < RTN level – 3 dBA). Finally, the definition of the three acoustic zones assumes that relaxation can be also achieved outside the 'relaxation zone', as tranquillity can be still improved for low levels of masking⁴ (i.e. in areas where water sounds are lower than RTN).

Results from sound maps are presented below by taking into account the preferences obtained from audio-visual tests¹⁵ in order to identify which types of water features are most effective for promoting relaxation as well as improving soundscape perception in the presence of specific road traffic noise levels.

3 RESULTS

3.1 Mapping water generated sounds

Predictions of sound pressure levels made for all water features selected are presented as sound maps and expressed in dBA based on a greyscale colour/pattern in which each shade of grey or pattern corresponds to a 5 dBA change in level (refer to Table 1 for acronyms and details of water features), as shown in Figure 4. These maps are presented in the ranking order based on preferences obtained from the audio-visual tests carried out in previous research.¹⁵

Results showed that the natural shallow stream (the only case tested in the field) generates levels of 49 dBA in proximity of the feature and 36 dBA at a distance of 20 m (Fig. 4(a)). Water sounds levels produced by a sawtooth edge waterfall (SEW), a plain edge waterfall (PEW) and a narrow jet (NJT) resulted comparable levels ranging from 45 to 71 dBA at respectively 20 m and 1 m from the water structures (Fig. 4(g)-(i)-(j)). Similarly, a small holes waterfall (SHW) generates sound levels ranging from 43 to 68 dBA at distance of 20 and 1 m respectively from the structure (Fig. 4(d)). A cascade with four steps (CA), a fountain with 37 upward jets (FTW), a dome (DF) and foam (FF) fountains generate comparable sound levels of around 61-66 dBA at the edge of the fountains and approximately 35-38 dBA at 20 meters from these water structures (Fig. 4(b)-(c)-(e)-(f)).

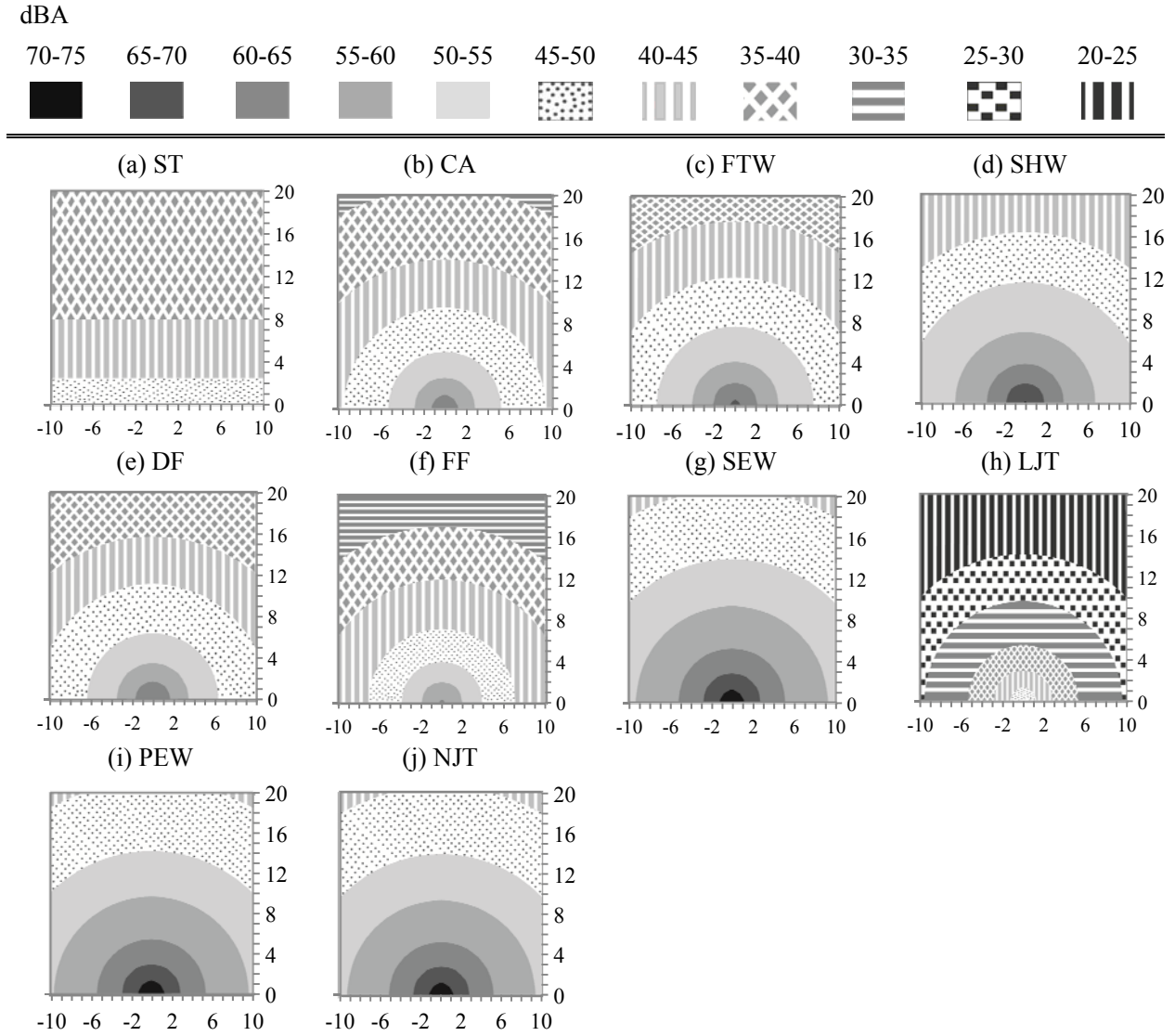


Fig. 4 - Sound mapping of water generated sounds over a grid of $20\text{ m} \times 20\text{ m}$ for all the water features tested. Sound maps are presented in the ranking order obtained from audio-visual perception tests.¹⁵ (a) Natural shallow stream (ST), (b) Cascade-4 steps (CA), (c) Fountain-37 upward jets (FTW), (d) Small holes waterfall (SHW), (e) Dome fountain (DF), (f) Foam fountain (FF), (g) Sawtooth edge waterfall (SEW), (h) Large jet (LJT), (i) Plain edge waterfall (PEW) and (j) Narrow jet (NJT).

Finally, a large jet (LJT) produces sound levels ranging from 21 to 41 dBA at respectively 20 m and 1 m distant from the fountain (Fig. 4(h)).

3.2 Mapping acoustic zones around water features used over road traffic noise

This part of the work aimed at identifying different levels of relaxation that can be achieved in different acoustic zones ('water sounds dominant zone', 'relaxation zone' and 'RTN dominant zone') around all the water features tested in the presence of road traffic noise (as already explained in section 2.3). Different noise settings which are characterised by sound levels of road

traffic noise ranging from 40 to 70 dBA were considered. This was chosen in order to evaluate typical acoustic settings where water structures can be located (40 dBA being quiet, 55 dBA being not too quiet and not too noisy and 70 dBA being noisy). In addition, road traffic noise levels were assumed to be continuous (i.e., dense road traffic noise) with no noticeable presence of major intrusive peaks such as passing vehicles. Results consist of sound maps where water features are located in the middle of the edge of a 20 m × 20 m grid (Figure 3), where the different acoustic zones have been colour coded (dark colour: 'RTN dominant zone', grey colour: 'relaxation zone' and light grey colour: 'water sound dominant zone'). In addition, results are only given for water features (ST, CA, FTW and SHW) with a positive audio-visual impact on preferences, i.e. features having been highly rated in audio-visual tests.¹⁵

Sound maps for water features used over a road traffic noise level of 40 dBA showed that the 'relaxation zone' extends 8 to 13 m from the baseline of the natural shallow stream (ST); this corresponds to an area of 14 to 17 m from a cascade with four steps (CA), while it is restricted to 18 to 23 m from the edge of a fountain with multiple upward jets (FTW) (Figure 5(a)). On the other hand, water sounds are dominant in the entire 20 m × 20 m grid around a waterfall with small holes edge (SHW) (Fig. 5(a)).

In the presence of a road traffic noise level of 45 dBA, the 'relaxation zone' extends 2 to 5 m from a natural shallow stream (ST), as shown in Figure 5(b). Relaxation can be promoted in an area corresponding to 9 to 12 m from the edge of a cascade (CA), while this extends 12 to 15 m from a fountain with multiple upward jets (FTW) (Figure 5(b)). In the case of SHW, the water sound is dominant up to 15 m from the waterfall and the relaxation area extends 16 to 21 m (Fig. 5(b)).

In a setting characterised by road traffic noise levels of 50 dBA, it can be noted that the 'relaxation zone' is restricted to up to 1 m from a natural shallow stream (ST), whilst this extends 5 to 7 m from a cascade with four steps (CA) (Figure 5(d)); and the area for relaxation expands 7 to 11 m from the fountain with multiple upward jets (FTW), and 11 to 14 from a small holes waterfall (SHW) (Fig. 5(d)).

In an acoustic setting with RTN levels of 55 dBA, results showed that the natural shallow stream (ST) cannot be used for generating sound levels comparable to RTN, meaning that no 'relaxation zone' can be found around these water features (Fig. 5(e)). For a cascade with four steps (CA), a 'relaxation zone' corresponds to an area 3 to 4 m distant from the edge of the structure, whilst it extends 4 to 6 m from a fountain with multiple upward jets (FTW) (Figure 5(e)). In the case of a small holes waterfall (SHW), relaxation can be improved at 5 to 7 m from the feature (Fig. 5(e)).

In addition, results showed that the natural shallow stream (ST) is not able to generate sound levels comparable to RTN levels louder than 55 dBA. However, a restricted area around CA, FTW and SHW was identified as the 'relaxation zone' (up to 2 m from CA, 3 m from FTW and 4 m from SHW) when they are used over RTN levels of 60 dBA. Furthermore, results showed that the 'relaxation zone' is restricted to a small area close to most of the water features tested in the presence of RTN 65 dBA (up to 1 m from CA, 1.5 m from FTW and 3 m from SHW). In acoustic settings with road traffic noise levels of 70 dBA, the 'relaxation zone' is limited up to 1 m from a small holes waterfall (SHW), whilst results suggested that CA and FTW were not effective to generate sound levels comparable to RTN. At these higher RTN levels, multiple water features should be used to obtain water sound levels that are high enough for masking road traffic noise.

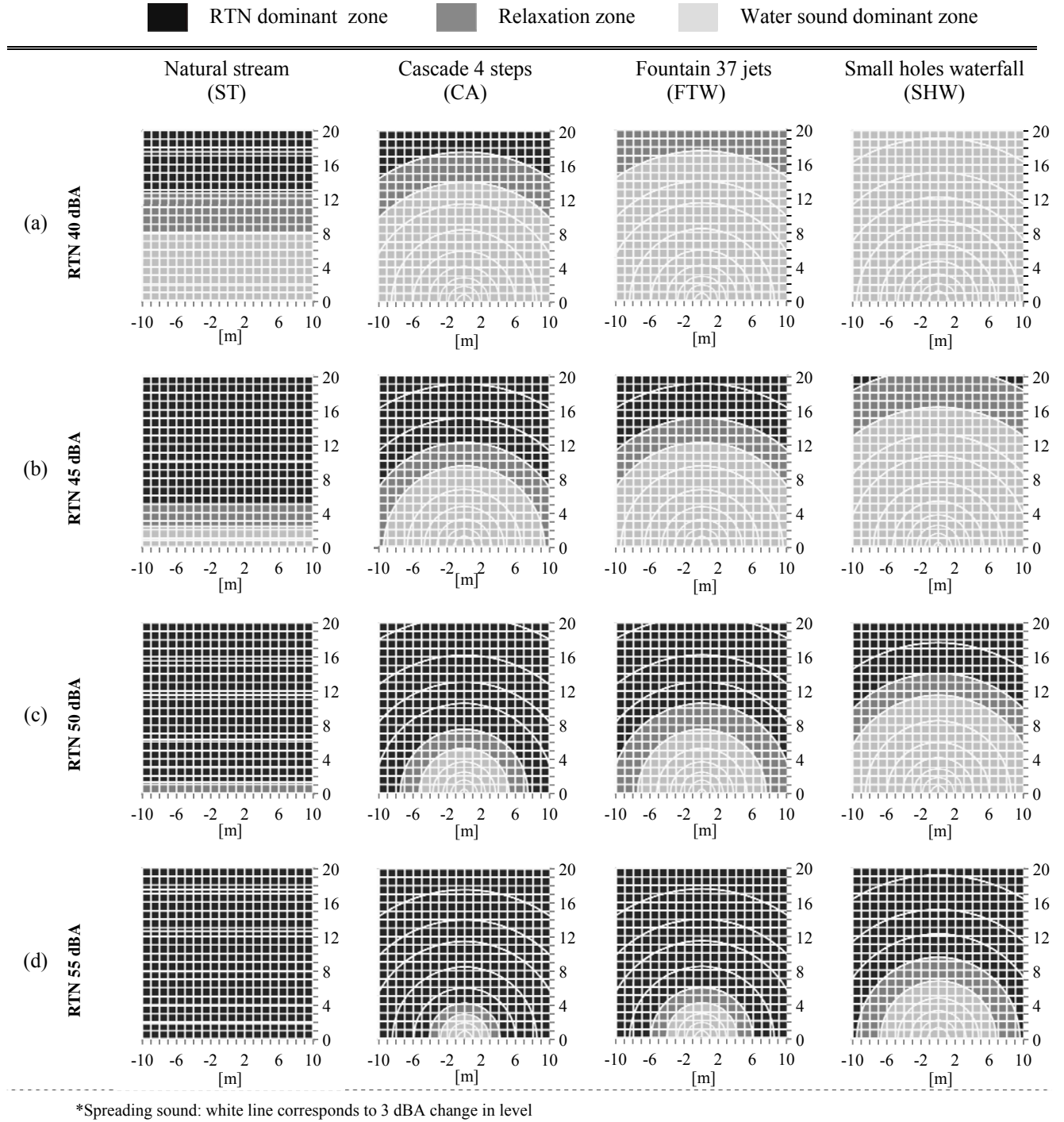


Fig. 5 - Sound mapping zones over a grid of 20 m x 20 m for the highly rated water features obtained from audio-visual preferences tests (1st to 4th ranking positions).¹⁵ Natural shallow stream (ST), Cascade-4 steps (CA), Fountain-37 upward jets (FTW) and Small holes waterfall (SHW).

4 CONCLUSIONS

Sound maps of individual water features showed that, for an area of 20 m × 20 m around the structure, sound pressure levels at the receiver vary in a range from 35 to 75 dBA for all the small to medium sized water features tested in the laboratory. It can be also observed that waterfalls are normally louder than fountains, jets and cascade. This was previously pointed out by Galbrun and Ali,⁹ who tested the water features used in the current study. On the other hand, predictions of sound pressure levels ranged from 36 to 49 dBA at respectively 20 and 1 m for the natural shallow stream tested in the field.

In order to identify the effectiveness of small to medium sized water features (waterfalls, cascades, fountains and streams) for promoting relaxation in the presence of road traffic noise, results of sound maps identified three acoustic zones ('RTN dominant zone', 'relaxation zone' and 'water sound dominant zone') where different levels of relaxation can be achieved, depending on the sound pressure levels of each type of water structures and the specific noise setting considered. Furthermore, it should be remembered that relaxation can also be promoted outside the boundaries of the 'relaxation zone', as tranquillity can be still achieved for low levels of masking.⁴

The analysis of the acoustic zones around a natural shallow stream showed that the relaxation zone extends up to 13 m and 5 m from the water structure in the presence of RTN 40 and 45 dBA respectively (whilst very small 'relaxation area' was found for a stream used over RTN 50 dB). This suggests that a natural shallow stream is mostly effective for promoting relaxation in quiet environments such as suburban areas (40-45 dBA) distant from main traffic routes, and tends to improve the soundscape perception, being the preferred feature identified in the audio-visual tests.¹⁵ Furthermore, cascades and fountains with multiple upward jets can produce sound levels comparable to road traffic noise levels ranging 40 to 60 dBA, meaning that these features might be used in acoustic environments characterised by quiet as well as relatively noisy levels (e.g. suburban areas as well as urban areas such as parks or squares) of road traffic noise. However, the 'relaxation zone' consists of a very small area around these water features for RTN levels of 60-65 dBA. In the case of a small holes waterfall, results suggest that it might be used to promote relaxation (having been positively rated in the audio-visual tests), as it can generate sound levels comparable to RTN levels from 40 to 65 dBA. Individual water features of small to medium size are therefore effective in promoting relaxation in areas where road traffic noise ranges between 40 to 60 dBA mainly. For higher road traffic noise levels, the use of multiple water features needs to be considered for achieving appropriate water sound levels.

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